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Period Changes in a Classical Cepheid ζ Geminorum Determined by the Phase-Dispersion Minimization

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The phase-dispersion minimization (PDM) method is applied to investigate the period change of a Cepheid variable, ζ Geminorum. The observational data from 1897 to 1979 are used and $[\Delta P/P]_{100} = -4.51(\pm 3.55) \times 10^{-4}$ is obtained. The result is in agreement with that of the O-C method. The validity of the PDM method for period changes is discussed.

Keywords: Cepheids, period change, stellar evolution, ζ Geminorum

§1. Introduction

In general, Cepheid variables seem to pulsate regularly and their period remains constant. Nevertheless, with the accumulation of observations, it is found that some of the variables change their pulsation period. In Cepheids these period changes are mainly attributed to stellar evolution.

Period changes of classical Cepheids were investigated by many authors: Nielsen[1], Parenago[2], Makarenko[3], Abt and Levy[4], Hoffleit[5], Szabados[6-8], Erleksova and Irkaev[9], Deasy and Wayman[10], Jerzykiewicz[11], and others.

In particular, Szabados[12] systematically investigated period changes of about 100 Cepheids using O-C diagrams and found about a half of Cepheids unstable in period. In addition, 15 among them undoubtedly showed parabolic O-C graphs, which are proof of continuous period changes. Furthermore, these observed period changes are in agreement with the theoretical values calculated from the stellar evolution theory (Hofmeister[13]). The investigation of Szabados verified the earlier results that the longer the pulsation period the larger the period changes (Parenago[2]) and that the period changes of the small amplitude Cepheids are larger than that of the normal ones (Makarenko[3]).

The tendency that the long-period Cepheids are unstable in period is also found in Magellanic Cloud Cepheids (Deasy and Wayman[10]).

The O-C diagrams have been long used for the period analysis. Now, are there other useful methods for the investigation of the period changes?

Fourier transformation and the maximum entropy method are well-known. These methods are, however, not very suitable for the analysis of the observed quantities, because in general the time intervals of the observed values are different each other and the number of the data per period is small. The method of phase-dispersion minimization (PDM), introduced by Stellingwerf[14], is well suited to the case of only a few irregularly spaced observations. We tried directly to obtain periods using this method and then investigated period change.

For the star we investigate using PDM, ζ Geminorum is chosen, because this Cepheid is bright and thus rich in the number of observations. Moreover the period of the star is relatively long, and therefore the period change is large, as mentioned above. So we may expect the detection of the period change is easy.

§2. Method

We used 736 published observational data of ζ Geminorum during 82 years from 1897 to 1979, which consist of photoelectric and visual observations. The sources of these data are shown in Table 1.

Table 1. Periods of ζ Geminorum by the PDM method

t (JD)	n	P (day)	weight	sources
241 4153	84	10.15127 ±305	0.33	1
241 7747	96	10.15158 ±245	0.41	2
241 9498	179	10.15226 ±56	1.79	2,3
242 2941	181	10.15437 ±57	1.75	4,5,6,7
242 5615	75	10.14945 ±96	1.04	7,8,9
243 4422	33	10.14978 ±256	0.39	10
243 8013	23	10.14718 ±110	0.91	10,11,12,13
243 9493	31	10.15011 ±268	0.37	12,14,15
244 3826	34	10.15268 ±183	0.55	16

sources

1. Pickering[17]
2. Nijland[18]
3. Luyten[19]
4. Leiner[20]
5. Rabe[21]
6. Nielsen[22]
7. Leiner[23]
8. Güssow[24]
9. Hall[25]
10. Mitchell et al.[26]
11. Williams[27]
12. Takase[28]
13. Wisniewski and Johnson[29]
14. Szabados[8]
15. Sudzius[30]
16. Moffett and Barnes[31]

t : average date of data group
n : number of data
p : period derived by PDM

An outline of the method by which we derive a period change from the data is as follows: first the sequence of data is divided into some groups by a given time interval; next PDM derives periods for each group, and thus we will obtain the periods as a function of date; finally the results are analyzed by the method of least squares, and we can find the amount of the period change.

There is some ambiguity to divide the data. The time interval of each group must be short so that the period during the interval can be regarded as a constant. However, excessively short interval will make the number of data in the group small. At least, 20 data are required to obtain the results with good accuracy. We adopted 3000 days for the time interval in the present study.

In the method of PDM aliased periods, for example subharmonics, can often appear (Stellingwerf[14]). Therefore, to prevent this troublesome phenomenon, the period was analyzed in the given frequency interval around the expected period of the star. Consequently we searched the deepest minimum in the range of frequencies between 0.098471 and 0.098571 day^{-1}.

The PDM method has Nb "bins", into which phase space is divided, and Nc "covers"; each cover is offset from the previous cover by 1/(NbNc) in phase. It is find that the value of the period obtained in the PDM technique is subject to the bin structure (Nb, Nc). Therefore, for the period we took an average value of ones obtained in 29 different bin structures:

Nc = 2, 3, 4, 5, 6, 8, and 10	for Nb = 4 and 5,
Nc = 2, 3, 4, 5, 6, and 8	for Nb = 6,
Nc = 2, 3, 4, 5, and 6	for Nb = 8,
and Nc = 2, 3, 4, and 5	for Nb = 10.

These bin structures were selected in consideration of accuracy, resolution and run time.

§3. Results

Assuming that the period of ζ Geminorum linearly changes as time passes, we calculated an amount of period change for the star by the method of weighted least squares. The values of periods averaged over 29 bin structures are weighted according to the standard deviations: that is, the weight will be inversely proportional to the standard deviation (see Table 1).

In this way, the period as a function of date is obtained as follows:

$$P = \begin{matrix} 10^{d}.154801 \\ \pm \quad 2762 \end{matrix} - \begin{matrix} 1^{d}.2548 \\ \pm\ 9884 \end{matrix} \times 10^{-7} \times (\mathrm{JD}-2400000)$$

The periods from each data group and the line fitted to the values are shown in Fig. 1.

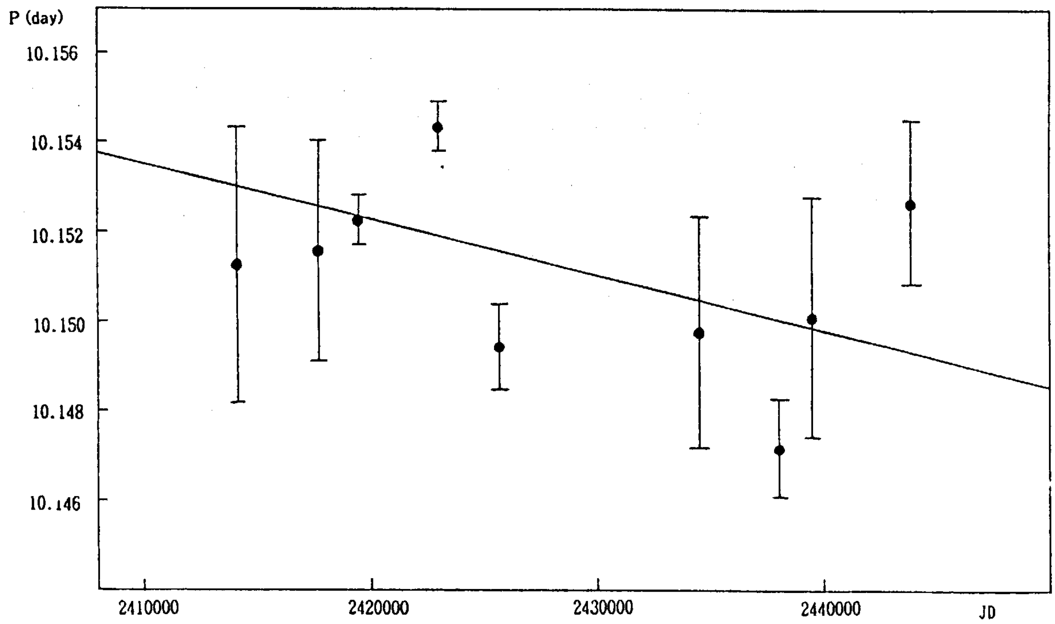

Fig. 1. The period change of ζ Geminorum. Points with error bars were obtained by the PDM method, and a straight line fitted to them by the method of weighted least squares is shown.

§4. Discussion

From the term of period change obtained above and its standard deviation, the period of ζ Geminorum is undoubtedly decreasing. There exists, however, certain scattering about the line which shows that period linearly changes as one can easily find in Fig. 1. In particular, deviations are remarkable in about JD 2423000 and about JD 2444000. Nevertheless, it can be considered that the period is linearly changing because the residuals are comparable to or smaller than the standard deviation. Therefore, this scattering may be properly caused by "period noise" (Szabados[12]) and/or accuracy of observations.

Table 2 shows comparison of this result with those of Nielsen[1], Parenago[2], Abt and Levy[4], Scarfe[15], Szabados[8], and Erleksova and Irkaev[9] in a common parameter $[\Delta P/P]_{100}$, which implies fractional period change during 100 years. In our result, the absolute value of period change is so large as one can easily find in Table 2, and moreover uncertainty is considerable (though this cannot be compared with all other results). The values of preceding results are distributed within the error of our value, therefore it may be concluded that PDM is valid to analyze the period change though it contains some problems, which are discussed later.

Secular period change is thought to be from the result of stellar evolution. The pulsation period of a Cepheid variable crossing the instability strip in the H-R diagram varies corresponding to the luminosity and the effective temperature. The period of ζ Geminorum is decreasing, and thus in

Table 2. Comparison of period changes in ζ Geminorum

Author	$[\Delta P/P]_{100}$ (10^{-4})	Years covered by observations	method
Nielsen	-4.07(±0.25)	1849-1927	O-C
Parenago	-3.59		O-C
Abt and Levy	-3.48		
Scarfe	-3.56(±0.09)		
Szabados	-3.71	1844-1978	O-C
Erleksova and Irkaev	-3.49		O-C
present paper	-4.51(±3.55)	1897-1979	PDM

the H-R diagram this star is crossing the instability strip from the right to the left. Therefore, the star is thought to be in the second crossing. Assuming an evolutionary track of the star, we may assume that the period is about 12 days when the star reached the red edge of the strip and about 6 days when it will leave the blue edge. According to the evolutionary calculation of Becker, Iben, and Tuggle[16], the star of 7 solar mass crosses the strip in 1.05×10^4 years ($Y = 0.36$, $Z = 0.02$) or 3.27×10^5 years ($Y = 0.20$, $Z = 0.02$) for second crossing. Therefore the fractional period change during 100 years is theoretically 5.6×10^{-3} or 1.8×10^{-4}, and the latter is in good agreement with observational values.

The PDM method is suitable for the analysis in computer. However, as mentioned above, the method has some problems.

First, the PDM method seems to be less accurate than the O-C method. The O-C values are obtained in every observed maximum (or median). When we have sufficient observations for determining the maxima or medians, this method works quite well. On the other hand, in the PDM method we tried, data are dealt with collectively in every time interval. Therefore, in the PDM the number of derived values cannot be large, and it is difficult to detect the variation of periods only appeared in a short time interval. Moreover, derived periods are occasionally strongly dependent on the bin structure. This is also one of factors which reduce the accuracy.

Although the PDM method has some disadvantage, the value from the PDM method is in agreement with that from the O-C method. Therefore when there are many data but maxima cannot be calculated because of sparse, fragmentary data, the PDM method may be valid.

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The computations were carried out on the ACOS 1000 system at the Computer Center of Tohoku University.

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